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Restoring longleaf pine wiregrass ecosystems: Hexazinone application enhances effects of prescribed fire

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Abstract

A longleaf pine wiregrass ecosystem in the sandhills of north central Florida, upon which turkey oak gained dominance following a wildfire, was treated with applications of hexazinone (1.1 or 2.2 kg/ha) in May 1991. All applications successfully reduced competition from oaks in the overstory and understory (mortality >80%), resulting in progressive increases in the foliar cover of wiregrass, all graminoids and forbs through time. Broadcast application caused a decline in forb cover and species richness during the initial growing season, which recovered by the following year. The 2.2 kg/ha spot application resulted in an increase in species richness, while evenness declined with the continuing expansion of wiregrass. The entire site was then burned in June 1995 by prescribed fire, which caused a widespread decrease in the cover of oaks, shrubs, wiregrass, all graminoids and forbs and plant species richness. In the following year, forb cover increased and oak cover remained significantly lower on plots treated with the combination of hexazinone plus fire than on fire-only plots. The overall cover of forbs, graminoids, shrubs and longleaf pines continued to increase through time. Broadcast application initially exposed a greater number of understory plants to direct contact with herbicide, posing a higher mortality risk than may be acceptable in restoration efforts. Although recovery occurred in subsequent years, the lower selectivity of broadcast application makes it a less suitable restoration technique. Spot application of hexazinone was more selective in its effects upon the plant community. The 2.2 kg/ha spot application produced increases in the cover of wiregrass, all graminoids and forbs and the highest levels of species richness and diversity. The 2.2 kg/ha application rate was also most effective in controlling woody plant competition and is therefore recommended for restoring longleaf pine wiregrass ecosystems in sandhills and similar environments. Hexazinone application followed by prescribed fire accelerates the rate of ecosystem restoration over that achievable by using fire alone. The ecological benefits of controlling competition and rebalancing floristic composition rapidly achieved through this combination of treatments would likely require many cycles of prescribed fire, if used as an individual treatment, over a period of several decades.

Keywords: *Pinus palustris* Mill.; *Aristida beyrichiana* Trin. & Rupr.; *Quercus laevis* Walt.; Foliar cover; Plant species diversity; Sandhills; Herbicide

1. Introduction

Although once among the most extensive ecosystems in North America (Landers et al., 1995), occupying 37 million ha in the southern United States prior to settlement (Frost, 1993), longleaf pine (*Pinus*

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pine wiregrass ecosystem (Boyer and White, 1990). Fire at intervals as frequent as 2–4 years may be beneficial in ecosystem restoration without need for measures to protect regeneration. Mechanical site preparation methods have also been proposed, but must be carefully applied to avoid adverse effects upon wiregrass (Clewell, 1989; Outcalt and Lewis, 1990; Outcalt, 1993). Herbicide application has also been suggested as a means of selectively reducing competing vegetation, favoring expansion of longleaf pine and wiregrass, minimizing physical disturbance of the soil and avoiding displacement of site nutrients (Wilkins et al., 1993a, b; Brockway et al., 1998).

A degraded longleaf pine wiregrass ecosystem, that had been invaded by scrub oaks following timber harvest and wildfire in the sandhills of north central Florida, was treated with hexazinone and burned 4 years later with prescribed fire. In measuring post-treatment changes in the foliar cover and species diversity of vascular plants over 7 years, the objectives of this study were to (1) evaluate hexazinone as a selective agent for controlling competition from invasive woody vegetation (primarily oaks), (2) measure the effects of hexazinone on non-target plant species (principally wiregrass, other grasses and forbs), (3) determine whether application of hexazinone can serve as a viable restoration treatment and (4) compare the effectiveness of hexazinone application followed by prescribed fire with that of prescribed fire alone for rebalancing interspecific competition and adjusting plant community structure when restoring longleaf pine wiregrass ecosystems in sandhills and similar environments.

2. Methods and materials

2.1. Study site

This experiment was conducted on the Lake George Ranger District of the Ocala National Forest in Marion County, north central Florida. The study site is located on Riverside Island (29°28′N, 81°50′W), one of the largest remaining longleaf pine wiregrass areas along the Mount Dora Ridge (Laessle, 1958). The climate is humid subtropical (Chen and Gerber, 1990). Annual precipitation is abundant, averaging 1300 mm, with more than half of this arriving during the June to September season (Aydelott, 1966). Average monthly temperatures range from 21 to 28°C for the April to October period and from 14 to 19°C for November to March (NOAA, 1930–1985).

The study area is approximately 50 m above sea level in a sandhills landscape with rolling topography, devoid of surface drainages and characterized by closed depressions. Surface slopes, ranging from nearly level (0–2%) to moderately inclined (up to 8%), are aeolian dunes which developed during periods of climate and sea level fluctuation in the Pleistocene (Kalisz and Stone, 1984). Surface deposits are comprised of sands 2–3 m thick overlying the stratified sand, gravel and kaolinitic clays of the Citronelle Formation (Laessle, 1958). Soils developed in parent materials devoid of easily weathered primary minerals and consist of quartz sand with small amounts of iron and titanium (Kalisz and Stone, 1984). Clay-sized particles are primarily quartz, kaolinite, hydroxy-aluminum interlayered minerals and gibbsite (Carlisle et al., 1978). Soils present on the site are excessively drained entisols and typically exhibit little if any profile development (Brown et al., 1990). The predominant soil is the Astatula series (Typic Quartzipsamments, hyperthermic) which is low in organic matter, nutrients and water holding capacity (Aydelott et al., 1975). This environment is commonly described as a 'wet desert' or 'desert in the rain' since, while precipitation is abundant, the soil can become extremely dry within 1 week without substantial rainfall (Outcalt, 1993).

Vegetation on this 'high pine' sandhills area was previously dominated by an overstory of longleaf pine, within a larger matrix of sand pine (Laessle, 1958; Myers, 1985, 1990; Myers and White, 1987). Evidence suggests that these have been the two principal ecosystems in this area for the past 5000 years (Watts, 1971; Watts and Hansen, 1988; Watts et al., 1992). However, the degraded nature of the study site was reflected in the relative absence of longleaf pine and predominance of turkey oak (*Quercus laevis*) with lesser amounts of sand pine, Chapman oak (*Quercus chapmanii*), sand live oak (*Quercus geminata*) and myrtle oak (*Quercus myrtifolia*). Associated understory shrubs included dwarf live oak (*Quercus minima*), saw-palmetto (*Serona repens*), scrub palmetto (*Sabal etonia*), rosemary (*Ceratiola ericoides*), crookedwood (*Lyonia ferruginea*), wax myrtle (*Myrica cerifera*), forest floor through defoliation (Michael and Boyer, 1983; Bouchard et al., 1985; Michael, 1985). Persistence in forest soils is relatively brief, with half-lives of 1–6 months in silt loam, 4–6 weeks in clay and <4 weeks in loamy sand (Rhodes, 1980; Sung et al., 1981; Lavy et al., 1989; Michael et al., 1990, 1999).

2.3. Measurements

In May 1991, plant cover was measured on all study plots to ascertain the pre-treatment status of the plant community. Repeated post-treatment measurements were then completed in September 1991–1993 and 1995–1997 to assess the ecological changes resulting from hexazinone application and prescribed fire. Total foliar cover (vertical projection of canopy) of all plant species was measured by line-intercept method along two permanent 20 m line transects (oriented north and south) within each treatment plot. Identification and nomenclature for plant species were consistent with taxonomic authorities (Bell and Taylor, 1982; Wunderlin, 1982; Clewell, 1985; Kurz and Godfrey, 1986; Godfrey, 1988; Foote and Jones, 1989; Grimm and Kartesz, 1993; Hall, 1993).

Foliar cover data for each species were summarized as estimates for each plot and analyzed by treatment and change through time. Foliar cover data were then used as importance values to compute numerous diversity indices (Ludwig and Reynolds, 1988). Species richness (total number of species present) and evenness (how abundance is distributed among species) are the two principal components of diversity. Species richness was characterized on each plot by counting the number of species present (N_0). Evenness (approaching one when all species are of equal abundance and declining toward zero when few species dominate) was determined through calculation of the modified Hill ratio (E_5). Diversity indices combine species richness and evenness into a single numeric value. Species diversity was estimated on all plots using the Shannon diversity index (H').

All data for dependent variables were summarized as estimates of the mean for each experimental plot. Each plot mean was then used to estimate the mean and variance for each of the hexazinone and/or fire treatments. For each dependent variable, a comparison of differences among experimental treatments and through the time sequence of repeated measurements was then undertaken. A repeated measures ANOVA, using initial conditions as covariates, was used to evaluate time and treatment effects and interactions (Hintze, 1995). Hexazinone plus fire treatment responses were compared to the fire-only treatment response using a set of three pairwise contrasts. The trend through time after treatment was analyzed using orthogonal polynomials. Statistical analysis of the time and treatment interaction for computed diversity indices was completed using the bootstrap technique PROC MULTTEST in SAS (Efron and Tibshirani, 1993; Westfall and Young, 1993; SAS Institute, 1996). Adjusted p-values, which maintain a constant Type I error across the full range of comparisons, were used to determine significant differences among means (10,000 bootstrap iterations were used). A probability level of 0.05 was used to discern significant differences.

3. Results

3.1. Foliar cover changes

The few residual adult and numerous seedling longleaf pines were unaffected by either the hexazinone application or the prescribed fire treatment (Table 1). Significant increases in the foliar cover of longleaf pine were observed on all treatments, except the 1.1 kg/ha spot application, by 1993 and on all treatments by 1996. Longleaf pine cover progressively expanded on all plots, exceeding 15% on the 1.1 kg/ha broadcast and 2.2 kg/ha spot treatments where the most rapid recovery of this principal overstory component was observed. Following hexazinone application in 1991, the foliar cover of turkey oak declined significantly, with the 1.1 kg/ha spot treatment causing an 82% decrease, the 1.1 kg/ha broadcast treatment causing a 90% decline and the 2.2 kg/ha spot treatment resulting in a 93% decrease. These foliar cover reductions for turkey oak persisted through the 1997 growing season with no evidence of recovery. During the same interval, turkey oak on the fire-only plots continued to expand its dominance, more than doubling its foliar cover. In 1995, the prescribed fire treatment caused a significant decrease in turkey oak cover on the fire-only plots; however, this decline was short-lived as turkey oak quickly recovered in

Table 1 (*Continued*)

Hexazinone (kg/ha)	0.0	1.1 broadcast	1.1 spot	2.2 spot	Adjusted mean[a]
Fall 1992	65.3	64.8	59.5	62.9	63.1[c]
Fall 1993	67.4	68.5	62.9	67.1	66.5[c]
Fall 1995	41.3	41.9	39.1	42.3	41.2[c]
Fall 1996	60.2	61.1	55.3	56.3	58.3[c]
Fall 1997	67.2	71.6	64.0	70.5	68.3[c]
Adjusted mean	64.7	62.1	55.4	55.2	
All graminoids					
Spring 1991	58.8	54.8	50.4	51.0	
Fall 1991	68.0	67.2	64.1	65.6	66.2[c]
Fall 1992	69.6	72.5	73.5	76.1	72.9[c]
Fall 1993	72.7	74.0	74.5	75.7	74.2[c]
Fall 1995	45.1	47.3	47.5	48.8	47.2[c]
Fall 1996	68.0	72.0	72.2	70.4	70.7[c]
Fall 1997	75.6	82.4	82.5	84.7	81.3[c]
Adjusted mean	63.7	68.7	70.9	71.7	
All forbs					
Spring 1991	4.5	7.2	5.0	3.0	
Fall 1991	7.3	3.2	8.5	5.3	6.1[c]
Fall 1992	9.3	12.8	10.0	9.1	10.3[c]
Fall 1993	7.4	14.8	10.8	10.1	10.8[c]
Fall 1995	3.4	3.7	3.2	3.0	3.4[c]
Fall 1996	11.6	20.3	10.9	16.1	14.7[c]
Fall 1997	7.8	14.7	12.4	15.0	12.5[c]
Adjusted mean	6.5	17.9[b]	9.6	4.5	

[a] Post-treatment mean adjusted by analysis of covariance.
[b] Significantly different from control (fire-only) plots, $p \leq 0.05$.
[c] Significant change through time from pre-treatment condition, $p \leq 0.05$.

1996 and continued its expansion through the 1997 growing season. A quite similar pattern was observed for all oak species combined. Hexazinone application significantly reduced the foliar cover of all oaks. On the fire-only plots, oak cover declined following prescribed burning, but then quickly recovered and, within 3 years, increased to levels exceeding the pre-treatment condition. The effect of hexazinone treatment on shrubs was less consistent, with only the 2.2 kg/ha application rate producing a significant decrease in shrub cover that lasted through the 1997 growing season. In 1995, prescribed fire caused a temporary significant decline in shrub cover on all plots. However in all cases, shrubs recovered rapidly during 1996 to pre-fire levels by 1997. Hexazinone application diminished the overall cover of woody plants from 1991 to 1993, by curtailing the rapid increase of oaks. Fire treatment in 1995 temporarily contributed to oak control on all plots. Although the foliar cover of woody plants recovered from prescribed burning by 1997, on hexazinone treated plots this resulted largely from the emergence of longleaf pine, while on fire-only plots it was due to the rapid expansion of oaks in combination with longleaf pine.

From 1991 to 1993, the foliar cover of wiregrass increased following hexazinone application at all rates (Table 1). Wiregrass cover expanded 23% on the fire-only plots, 41% on the 1.1 kg/ha broadcast treatment, 43% on the 1.1 kg/ha spot treated plots and 86% on the 2.2 kg/ha spot treatment. In 1995, prescribed fire caused significant decreases on all plots, but wiregrass recovered rapidly during 1996 to reach its greatest coverage in 1997. Although wiregrass cover increased over time more rapidly on hexazinone treated plots than on fire-only plots, when adjusted for initial season. By 1992, plant species richness fully recovered on the broadcast application plots and continued to increase on the spot treated plots, exceeding the 20 species present. In 1995, prescribed fire caused a decline in species richness on all plots, but this decrease was significant only for the 1.1 kg/ha broadcast application. By 1996, species richness recovered on all plots, reaching its highest values. In 1997, plots receiving the 2.2 kg/ha spot application followed by prescribed fire contained as many as 25 species, while those treated with fire-only typically supported about 20.

All hexazinone application rates resulted in non-significant declines in plant diversity during the first post-treatment growing season (Table 2). The largest of these was a decrease in the Shannon diversity index (H'), from 1.49 to 0.99, for the 1.1 kg/ha broadcast application. Alpha diversity declines for the spot applications were typically from 1.51 to 1.25. Diversity values on broadcast treated plots were comparable to those on untreated control plots, while those on spot treated plots were somewhat higher. During 1992 and 1993, species diversity recovered on all plots, approaching values averaging 1.40. In 1995, prescribed fire produced non-significant declines in diversity for all treatments, followed by abrupt increases in 1996 that continued through 1997. Plant diversity increases in 1996 and 1997 were significant only for the 2.2 kg/ha spot treatment and the fire-only treatment.

Only the 2.2 kg/ha spot application of hexazinone significantly affected plant species evenness during the first and all subsequent growing seasons through 1997 (Table 2). The high mortality rate among oaks and great increase in the cover of wiregrass associated with this treatment likely account for this sustained decrease in the modified Hill ratio (E_5) from 0.60 in 1991 to 0.43 by 1997. All other treatments appear to have little influence upon species evenness, except for the fire-only treatment. On these plots, plant species evenness significantly increased from the 1993 level of 0.47 to 0.56 in 1995 and then returned to a pre-fire level of 0.46 in 1996. This temporary increase appears related to a significant decline in shrub cover on fire-only plots during 1995, thus providing a brief season of greater equity in species distribution prior to the resumption of vigorous growth by woody plants in 1996.

4. Discussion

4.1. Effects on foliar cover

Neither hexazinone nor fire adversely affected the relatively rapid increase of longleaf pine. With exception of the 1.1 kg/ha spot application, longleaf pine cover was generally greater on plots treated with hexazinone plus fire than on the fire-only plots. Although studies elsewhere report that longleaf pine is subject to injury by growing-season fire (Boyer, 1990a, b), the progressive increase in longleaf pine cover on this study site suggests that such was not the case here. While not specifically measured, the growth losses attributed to prescribed fire treatment in earlier studies (Cary, 1932; Garren, 1943; Boyer, 1987, 1994; Landers et al., 1995) were not apparent on this site.

Hexazinone application on this xeric sandhills site greatly reduced the foliar cover of turkey oak and other oaks that had begun to dominate the longleaf pine wiregrass ecosystem. Similar results have been reported for higher-rate hexazinone applications ($\leq$6.8 kg/ha) on sandhills (Wilkins et al., 1993a) and lower-rate applications (0.3, 0.6 and 0.9 kg/ha) on well-drained uplands (Long and Flinchum, 1992). Initial turkey oak mortality rates, ranging from 82 to 93%, indicate that hexazinone application may be useful in selectively shifting the balance of competition for site resources to favor desirable plant species in the understory and overstory (Wilkins et al., 1993b; Brockway et al., 1998). Although shrub cover was initially decreased only by the spot applications, the overall early decline of woody plants appeared to have created opportunity for expansion of plants already occupying the site and liberated microsites where additional species might colonize.

While prescribed fire on the fire-only treatment did produce a pronounced decrease in oaks similar to that reported elsewhere (Rebertus et al., 1989a, b; Glitzenstein et al., 1995), the foliar cover of oaks rapidly increased in subsequent years, indicating that this brief decline would be short-lived. This result concurs with reports concerning the relatively minor effects of a single fire event in sandhills and similar environments (Abrahamson and Abrahamson, 1996a, b; Liu et al., 1997). Prescribed fire also caused a widespread decrease in shrub and woody plant cover, similar to that reported in previous studies (Moore et al., 1982;

hexazinone into close physical contact with nearly all plants and can be largely attributed to decreases in the cover of turkey oak and several forbs. Richness then recovered in the following year to pre-treatment levels. The number of species on spot treated plots was unaffected by the less uniform distribution of hexazinone which impacted fewer understory plants here than on broadcast treated plots (Brockway et al., 1998). These findings concur with reports of plant species numbers being unchanged or slightly higher during the second and subsequent growing seasons following herbicide application (Blake et al., 1987). Species richness showed an overall linear increase through time for all treatments, until prescribed fire produced universal declines in the number of species during 1995. Of these, the only significant decrease was again noted on the broadcast treated plots. The recovery of richness following both hexazinone application and prescribed fire treatments was largely related to a resurgence of forb species during subsequent growing seasons. This positive response by forbs is unlike that reported on other xeric sandhills where higher hexazinone application rates resulted in declining herbaceous plant diversity (Wilkins et al., 1993b).

Nonsignificant decreases in plant species diversity were observed for all hexazinone treatments in the initial growing season after application, followed by recovery to pre-treatment levels during the next year. This response pattern is similar to that reported for single applications of herbicide used for site preparation, where initial depression of diversity is followed by recovery along a trajectory similar to that of an untreated site (Neary, 1991). While the reduction in diversity on the broadcast treated plots resulted from lower levels of species richness, the decline on the spot treated plots was largely attributed to decreases in evenness among plant species. Decreased plant species evenness resulted from the increasing dominance of wiregrass following the reduction of turkey oak. In 1995, prescribed fire produced minor declines in diversity and left evenness unaffected on all except the fire-only plots. On these, evenness was temporarily increased when shrubs were substantially reduced by fire, but returned to pre-treatment levels shortly thereafter. This short-lived increase in evenness indicated that the fewer remaining species were more equitably distributed across the site. Increases in species diversity during subsequent growing seasons were largely a product of increasing species richness, mostly from increasing forbs and grasses.

Sandhills have been characterized as ecosystems dominated by scrub vegetation of low species diversity, whose structure and function reflect adaptations for survival in an environment characterized by seasonal water deficits, periodic fires and low soil fertility (Snedaker and Lugo, 1972). However, the presence of 95 plant species on this site is typical of the high vascular plant diversity of longleaf pine ecosystems (Peet and Allard, 1993). Plant species diversity is largely determined by interspecific competition interacting with site productivity, microsite heterogeneity and disturbance regimes (Tilman, 1982). Hexazinone, by causing selective mortality among different groups of plants, altered the competitive relationships among species and thus influenced plant diversity dynamics. Herbaceous plant diversity is reported to initially increase and subsequently decline to predisturbance levels on sites disturbed by prescribed fire, tree harvest or site preparation (Swindel et al., 1984; Lewis et al., 1988). Fire typically creates a diverse understory with high numbers of grasses, legumes and forbs (Waldrop et al., 1992) by reducing the shrub layer (Abrahamson and Hartnett, 1990), clearing microsites for herbaceous colonization and expansion (Moore et al., 1982) and stimulating the production and dissemination of reproductive propagules (Biswell and Lemon, 1943; Platt et al., 1988b; Landers et al., 1990; Streng et al., 1993; Outcalt, 1994b).

4.3. Restoring the ecosystem with hexazinone and fire

The close association of longleaf pine wiregrass ecosystems with periodic fire has been long recognized (Cary, 1932; Garren, 1943; Bruce, 1947; Komarek, 1968; Taylor, 1974; Veno, 1976; Christensen, 1981; Wright and Bailey, 1982; Abrahamson, 1984) and the need for frequent growing season fire to restore and sustain a wide range of resource values has been recently advocated (Noss, 1989; Rebertus et al., 1989b; Landers et al., 1990, 1995; Wade and Lundsford, 1990; Streng et al., 1993). This ecosystem occupies a portion of the Southeast that is highly prone to lightning with a high potential for wildfire ignition (Paul et al., 1968; Paul and Waters, 1978). Indeed, the

Fig. 1. Scarce oak and prominent longleaf pine and wiregrass after sequence of hexazinone application followed by prescribed fire treatment.

Fig. 2. Continuing oak dominance following prescribed fire-only treatment.

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